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1. Your reference MPS/7133

2. Patent applic... **9903597.4** 18 FEB 1999
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3. Full name, address and postcode of the or of each applicant *(underline all surnames)*
Oxford Fiber Optic Tools Limited
~~University of Warwick Science Park,~~
~~Barclays Venture Centre, Sir William Lyons Road,~~
~~Coventry, CV4 7EZ.~~ FASTON SCIENCE PARK
LOVE LANE
BIRMINGHAM B7 4BJ

23/4/77 10/77

Patents ADP number *(if you know it)* 676061500~~2~~3.

If the applicant is a corporate body, give the country/state of its incorporation United Kingdom

4. Title of the invention
Fibre Optic Grating Sensor

5. Name of your agent *(if you have one)* Swindell & Pearson

"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*
48 Friar Gate,
Derby DE1 1GY

Patents ADP number *(if you know it)* 00001578001

6. If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and *(if you know it)* the or each application number

Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*

7. If this application is divided or otherwise derived from an earlier UK application, give the number and the filing date of the earlier application

Number of earlier application	Date of filing *(day / month / year)*

8. Is a statement of inventorship and of right to grant of a patent required in support of this request? *(Answer 'Yes' if:* Yes
a) any applicant named in part 3 is not an inventor, or
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Description	10
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Statement of inventorship and right to grant of a patent *(Patents Form 7/77)*	
Request for preliminary examination and search *(Patents Form 9/77)*	
Request for substantive examination *(Patents Form 10/77)*	
Any other documents *(please specify)*	

11. I/We request the grant of a patent on the basis of this application.

Signature Swindell & Pearson Date 17/02/99

Swindell & Pearson

12. Name and daytime telephone number of person to contact in the United Kingdom Mr. M.P. Skinner - 01332 367051

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Fibre Optic Grating Sensor

This invention relates to a fibre optic grating sensor, particularly but not exclusively a fibre optic grating strain or temperature sensor.

It is known that fibre Bragg gratings may be used as a tool for measuring, for example, temperature and strain. The grating is formed in the fibre to reflect light at a wavelength which is determined by the physical characteristics of the grating. A change in the temperature and/or strain applied to a fibre Bragg grating changes the period of the grating and hence the wavelength of the light reflected by the grating. Arrays of fibre Bragg gratings, in which the gratings are spatially separated along a length of fibre and the spectral profiles of the gratings are separated in wavelength, have been used to measure strain and temperature gradients by illuminating the array with broadband light and measuring the wavelength of the reflected light. A measurement of the wavelength shift (if any) provided by each grating provides information about the strain or temperature at that grating. Using a grating array to make a quasi-distributed strain or temperature measurement along a short length (about 5cm or less) requires the fabrication of grating arrays comprising gratings of very short spatial length (generally less than 4mm). For short length arrays, the spatial separation between adjacent gratings often becomes comparable to the spatial length of the gratings. In order to increase the number of gratings within the array the length of the gratings must be decreased, which rapidly increases the spectral bandwidth of the grating and hence reduces the spectral resolution of the sensor.

It is an object of the present invention to provide an improved fibre optic grating sensor.

According to the present invention there is provided a fibre optic grating sensor comprising an optical fibre having a grating portion along which the refractive index of the fibre varies periodically, the periodic variation having an amplitude envelope which includes at least one region in which the amplitude

of the envelope is substantially reduced, the said variation giving the grating portion a spectral profile within which there is at least one pass band.

Preferably, the amplitude envelope includes at least one region in which the amplitude of the envelope is substantially nulled. The amplitude envelope preferably includes a plurality of regions in which the amplitude of the envelope is substantially nulled. Each null region desirably gives rise to a corresponding pass band. Adjacent null regions, and hence adjacent sensors, are desirably spatially separated. Preferably each sensor is independently actuable and hence the wavelengths of the corresponding pass bands are independently variable.

The grating portion preferably comprises two substantially superimposed fibre Bragg gratings. The amplitudes of the refractive index profiles of the two gratings preferably add together to form the amplitude envelope.

The fibre Bragg gratings are preferably chirped fibre Bragg gratings. Desirably, the two chirped gratings have substantially the same rate of chirp and substantially the same spectral bandwidth, the first chirped grating having a different central wavelength to the second chirped grating. Alternatively, the first chirped grating has a different rate of chirp to the second chirped grating, and the two chirped gratings have substantially the same central wavelength and bandwidth.

Alternatively, the fibre Bragg gratings may be linear fibre Bragg gratings. The two linear gratings preferably have substantially the same spectral bandwidth. Desirably the first linear grating has a different central wavelength to the second linear grating.

The grating portion may alternatively comprise one fibre Bragg grating having a plurality of regions within which the refractive index profile of the grating is substantially reduced or nulled.

The fibre Bragg gratings are preferably fabricated using a known two-

beam interference holographic fabrication method. Alternatively, the fibre Bragg gratings may be fabricated using a known phase-mask fabrication method.

The null regions in the single fibre Bragg grating are desirably formed in a fibre Bragg grating fabricated using the two-beam interference holographic fabrication method by providing an amplitude mask generally in front of the fibre, generally in the beam paths, during fabrication. Alternatively, the null regions in the single fibre Bragg grating may be formed in a fibre Bragg grating fabricated using the two-beam interference holographic fabrication method or the phase-mask fabrication method by subsequently further exposing regions of the grating. The single fibre Bragg grating may be a linear grating or a chirped grating.

The grating portion may further alternatively comprise a single grating structure fabricated using the phase-mask fabrication method. The desired grating structure is preferably represented on a phase-mask and subsequently inscribed into the fibre through the phase-mask. Alternatively, the grating structure may be inscribed in the fibre through a phase-mask, the fibre undergoing oscillating motion, along its longitudinal direction, relative to the phase-mask to thereby control the refractive index profile within the grating structure. The phase-mask may alternatively or additionally undergo oscillating motion relative to the fibre.

The optical fibre is preferably photosensitive enhanced optical fibre. The photosensitive enhanced optical fibre may be germania doped optical fibre, or boron-germania co-doped optical fibre. The germania doped fibre may be hydrogen loaded to further increase the photosensitivity of the fibre. The boron-germania co-doped fibre may be hydrogen loaded to further increase the photosensitivity of the fibre. The photosensitive enhanced optical fibre may alternatively be hydrogen loaded standard optical fibre. The hydrogen loaded fibre may be annealed following fabrication of the grating structure to substantially remove any residual hydrogen from the fibre.

The grating structure may further alternatively comprise a side-etched surface-relief grating structure, preferably fabricated in standard optical fibre.

The fibre grating sensor may comprise a plurality of grating portions.

A specific embodiment of the invention will now be described by way of example only, with reference to the accompanying drawings, in which:

Figure 1(a) is a diagrammatic representation of a fibre optic grating sensor according to the present invention, comprising a Moiré grating;

Figure 1(b) is a diagrammatic representation of the theoretical refractive index profile of the Moiré grating of figure 1(a);

Figure 1(c) is a diagrammatic representation of the theoretical spectral profile of the Moiré grating of figures 1 (a) and (b);

Figure 2 shows the optical spectrum of a 10-pass band Moiré grating constructed according to the invention;

Figure 3 shows linear-strain-gradient measurements taken using the grating of figure 2; and

Figure 4 shown exponential-temperature-gradient measurements taken using an 8-pass band Moiré grating constructed according to the invention.

Referring to the drawings, there is provided a fibre optic grating sensor 10 comprising an optical fibre 12 in which a grating portion 14 is provided, the refractive index 16 of the fibre 12 varying periodically along the grating portion 14. The periodic variation of the refractive index 16 has an amplitude envelope which includes, in this example, two regions 24 in which the amplitude of the envelope is substantially reduced, and in this example is substantially nulled. The null regions 24 give the grating portion a spectral profile 20 within which there are, in this example, two pass bands 18.

While it is preferred that the amplitude envelope includes regions 24 in which the amplitude of the envelope is substantially nulled, it is sufficient that the amplitude of the envelope is merely significantly reduced. That is to say,

the amplitude of the envelope must be sufficiently reduced to give rise to identifiable, and measurable, pass bands 18 within the spectral profile 20 of the grating portion 14. The pass bands 18 are required to be identifiable one from the other, and from any light present at other wavelengths.

In this example, the grating portion is a Moiré grating formed by the notional or actual superimposition of two Bragg gratings. Each Bragg grating is "chirped". That is, the period of the grating changes along its length, either in linear fashion, or in a more complex manner. The wavelength reflected by a chirped-period, or "chirped" grating will vary along the length of the grating. The variation will be linear in the case of linear chirp, and more complex in other cases. By contrast, a linear grating reflects substantially the same wavelength along the length of the grating. A chirped grating has a broader spectral bandwidth than a linear grating of the same length.

The Moiré grating 14 is fabricated using a known two-beam interference holographic fibre grating fabrication method. Two chirped-period fibre Bragg gratings are inscribed in the same section of fibre 12 by two sequential inscribing operations. The two chirped gratings are of substantially the same physical length and have substantially the same spectral bandwidth. However, the central wavelength of the first chirped grating is slightly shifted in wavelength relative to the central wavelength of the second chirped grating. The amplitudes of the refractive index profiles of the two superimposed chirped gratings add together to produce the refractive index profile 16 of the Moiré grating 14 and thereby form the amplitude envelope of the refractive index profile 16 along the fibre.

Figure 1 illustrates how the refractive index profile 16 of a chirped Moiré grating 14 gives rise to pass bands 18 within the bandwidth of the spectral profile 20 of the Moiré grating 14, and to sensors 22 within the core of the optical fibre 12. In the regions within the amplitude envelope where nulls 24 occur, the grating strength is nulled. Where the grating strength is nulled no light is reflected by that region of the grating 14, and hence pass bands 18 are

created.

The regions within the fibre core where the nulls 24 in the amplitude envelope, and in the grating strength, occur may act as sensors 22. The length of a sensor 22 is the length within the fibre core in which the grating strength is substantially reduced or nulled. The spectral profiles of the sensors 22 are therefore the spectral profiles of the pass bands 18. The spectral bandwidth of the pass bands 18 is determined by the strength and chirp-rate of the Bragg gratings which form the Moiré grating 14.

The exact position of each sensor 22 can be calculated from the spectral profile 20 of the Moiré grating 14, knowing the exact length of the Moiré grating 14 and the manner in which the grating is chirped. The approximate length of each sensor 22 can be calculated using the full width half maximum spectral bandwidth of the pass bands 18.

Each sensor 22 occurs at a respective position in wavelength space and is independently actuable. Consequently each pass band 18 is independently variable in wavelength, within the bandwidth of the spectral profile 20 of the Moiré grating 14, in accordance with the value of the parameter being measured at the site of the corresponding sensor 22.

Figure 2 shows the spectral profile 30 of a chirped Moiré grating which comprises 10 pass bands 32. The Moiré grating was fabricated using the two-beam interference holographic method. A frequency doubled Argon Ion laser of wavelength 244nm was used and the Moiré grating was fabricated in hydrogen loaded germania doped optical fibre, such as that manufactured by Spectran. A first chirped fibre Bragg grating was fabricated having approximately 70% reflectivity, then a second chirped fibre Bragg grating of slightly different central wavelength was inscribed in the same piece of fibre. The wavelength shift between the two chirped gratings is 2nm. The magnitude of the wavelength shift determines the number of pass bands 32 in the Moiré grating.

The length of the Moiré grating of Figure 2 is approximately 6mm. The total spectral bandwidth is 12.6nm. The average bandwidth of the pass bands 32 is 0.39nm and the finesse is approximately 2.5. The approximate sensor length is less than 200μm.

Figure 3 shows strain measurement results taken using the 10 peak Moiré grating of figure 2. The measurements show how the strain varies along the length of the Moiré grating. The Moiré grating was bonded into grooves on a piece of spring steel (not shown). The steel was bent using a 4-point bending rig in order to effect a linear strain gradient along the Moiré grating. Figure 3 shows the strain measurements taken using the Moiré grating with the steel plate bent by three different amounts, to produce three different strain gradients.

The wavelengths of the pass bands 32 were measured in transmission using a tuneable laser and optical spectrum analyser, giving a measurement resolution of 0.01nm. The light from the tuneable laser was launched into a fibre grating sensor 10 comprising the 10 pass band Moiré grating and light transmitted by the Moiré grating was detected and measured using the optical spectrum analyser. The wavelength of the tuneable laser was tuned across the spectral bandwidth of the Moiré grating in order to interrogate in turn the sensor corresponding to each pass band 32.

The change in the central or peak wavelengths of the pass bands 32, between the unstrained starting state and the strained states, is calculated. The equivalent axial strain on each sensor is then calculated from the fractional change in the central wavelength (λ_B) of the corresponding pass band 32 of each sensor, using:

$$\Delta\lambda_B/\lambda_B = (1-p_e)\,\varepsilon$$

where p_e is the effective photosilicate constant, which is 0.22 for germanosilicate fibre, and ε is the applied axial strain.

The measurements 34 recorded for the steel plate bent by a first amount indicated that a linear strain gradient of 12.1$\mu\varepsilon$/mm was present across the Moiré grating. The measurements 36 recorded for the steel plate bent by a second amount indicated that a linear strain gradient of 23.4$\mu\varepsilon$/mm was present across the Moiré grating. The measurements 38 recorded for the steel plate bent by a third amount indicated that a linear strain gradient of 38.2$\mu\varepsilon$/mm was present across the Moiré grating.

The measurements recorded using this 10 pass band Moiré grating have a strain resolution of 8$\mu\varepsilon$ and a spatial resolution of approximately 450μm.

Figure 4 shows exponential temperature gradient measurements taken using a 8 pass band Moiré grating. The grating was fabricated using the two-beam interference holographic method, as described above. The spectral bandwidth of the Moiré grating is 12.8nm and the wavelength shift between the two chirped gratings is 2.5nm. The measurements show how the temperature varies along the length of the Moiré grating. One end of the Moiré grating was bonded horizontally to a hot plate, to provide an exponentially decaying temperature gradient with distance away from the hot plate, and along the Moiré grating.

The Moiré grating was interrogated generally as described above, using a broadband Erbium fluorescence source and an optical spectrum analyser, giving a measurement resolution of 0.08nm which corresponds to a temperature resolution of approximately 6°C. The change in the central wavelength (λ_B) is calculated for each pass band. The equivalent axial temperature is then calculated using:

$$\Delta\lambda_B/\lambda_B = (a + \xi)\Delta T$$

where a is the thermal expansion co-efficient of the optical fibre (0.55×10^{-6} for fused silica), ξ is the thermo-optic coefficient (approximately 8.3×10^{-6} for germania-doped silica) and ΔT is the applied temperature change.

By way of comparison, a linear fibre Bragg grating of the same length (200 μm), with a maximum transmission loss of 7dB, would have a full width half maximum spectral bandwidth of more than 5nm. Hence an array of ten such linear gratings would have a spectral bandwidth of more than 50nm. Use of, for example, the 10 pass band Moiré grating therefore reduces the required operating spectral bandwidth by more than 40nm.

The sensor length can be considered to be very short. Because the nulls in the refractive index profile define the pass band, this allows quasi-point measurements to be made and thus provides for high spatial resolution measurements. This short sensor length also enables a large number of measurements, of for example strain or temperature, to be taken over a small distance, such as 5-20mm, and within a single grating structure. Thus a greater spatial and spectral resolution is provided than for an equivalent number of discrete linear fibre Bragg gratings. Both linear and non-linear gradients of a chosen measurand can be measured.

Various modifications can be made without departing from the scope of the invention. For example, the grating portion may be a different type of grating to that described, and may be fabricated in a single step, for instance by using a known phase-mask fabrication method or a known side-etched surface-relief grating fabrication method. Using the phase-mask fabrication method, the grating portion structure may be represented on a phase-mask and directly inscribed in the fibre through the phase-mask. Alternatively, the grating portion may be inscribed in the fibre through a phase-mask, the phase-mask and/or the fibre being oscillated along their longitudinal direction during fabrication to thereby control the refractive index profile within the grating portion.

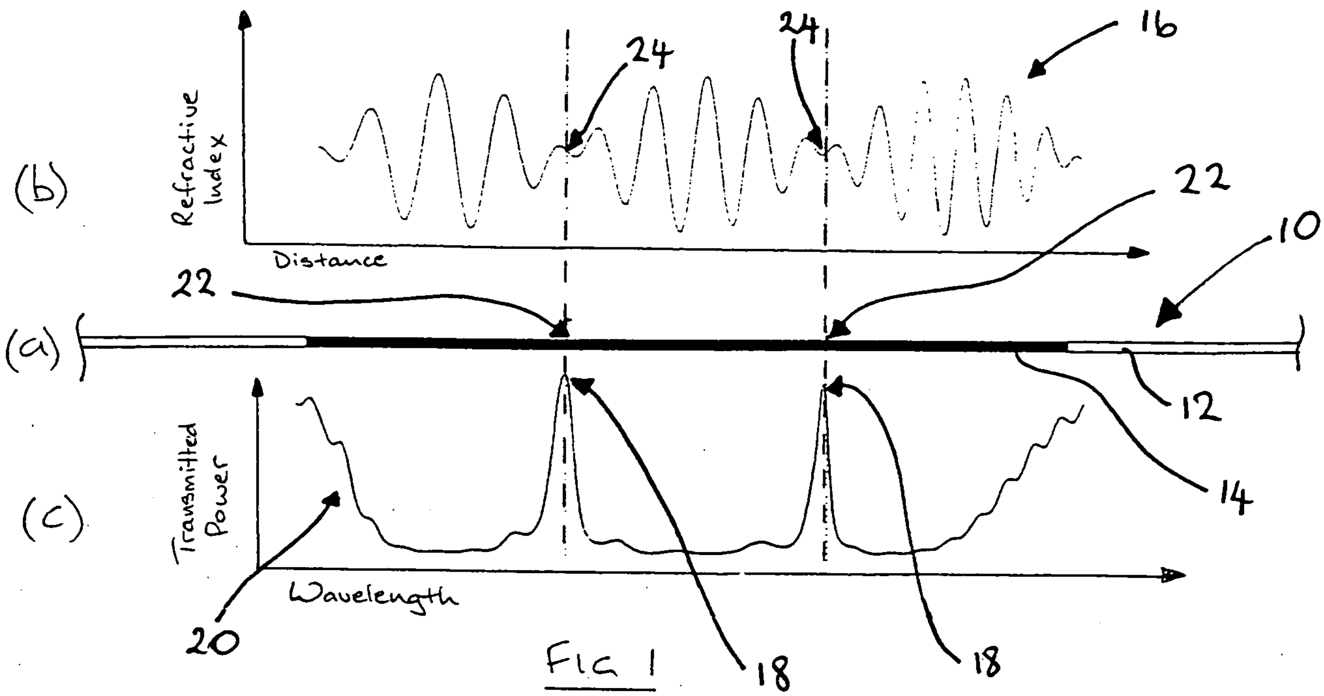
The Moiré gratings can be formed as two superimposed Bragg gratings of different central wavelength or chirp. Two gratings which vary slightly in bandwidth and/or central wavelength and/or chirp rate and/or the amount of physical overlap between the gratings will give rise to periodic nulls when

superimposed, and are thus likely to be of use in sensing applications. Alternatively, the profile of the Moiré grating could be devised to provide a plurality of nulls, without necessarily being reproducable by superimposing two gratings. Thus, the invention extends beyond the use of Moiré gratings, which would conventionally be considered to be the result of the superimposition of two grating structures. The grating structure may also be a single linear or chirped fibre Bragg grating in which parts of the grating are amplitude masked out during fabrication or are erased by further exposing sections of the grating following fabrication.

It will be appreciated that the grating structure may be fabricated in many different types of photosensitive enhanced optical fibre, other than that described, including Boron-germania co-doped fibre, and hydrogen loaded standard fibre. It will also be appreciated that the grating structures can be fabricated at a wide range of different central wavelengths, to suit a particular optical source and optical detector. This will to some extent affect which type of fibre the grating structure is fabricated in.

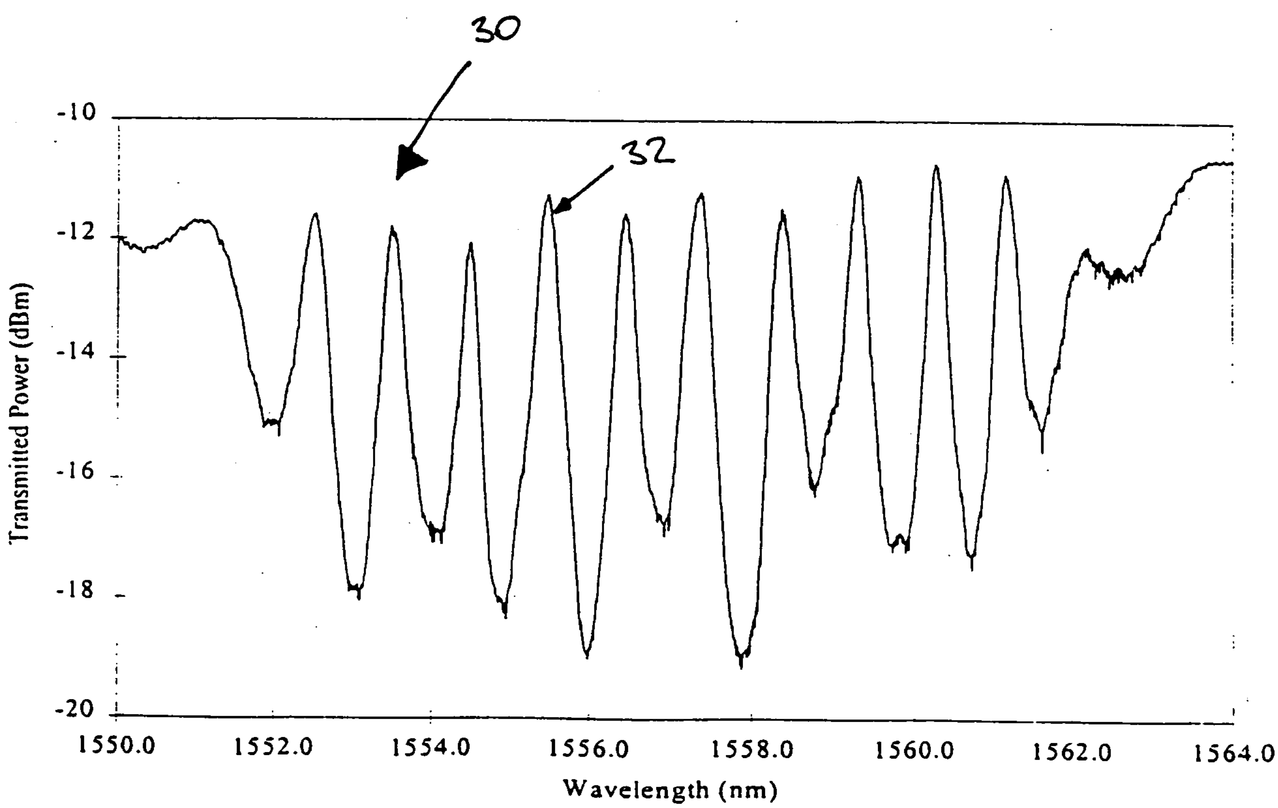
Grating portions of different length, bandwidth and number of pass bands may be used. More than one grating portion may be provided within a fibre grating sensor.

Whilst endeavouring in the foregoing specification to draw attention to those features of the invention believed to be of particular importance it should be understood that the Applicant claims protection in respect of any patentable feature or combination of features hereinbefore referred to and/or shown in the drawings whether or not particular emphasis has been placed thereon.



(b)
Refractive Index
Distance
24
24
16
22
22
10
(a)
12
14
Transmitted Power
(c)
Wavelength
20
18
18

Fig 1



30
32
-10
-12
-14
-16
-18
-20
Transmitted Power (dBm)
1550.0
1552.0
1554.0
1556.0
1558.0
1560.0
1562.0
1564.0
Wavelength (nm)

Fig 2

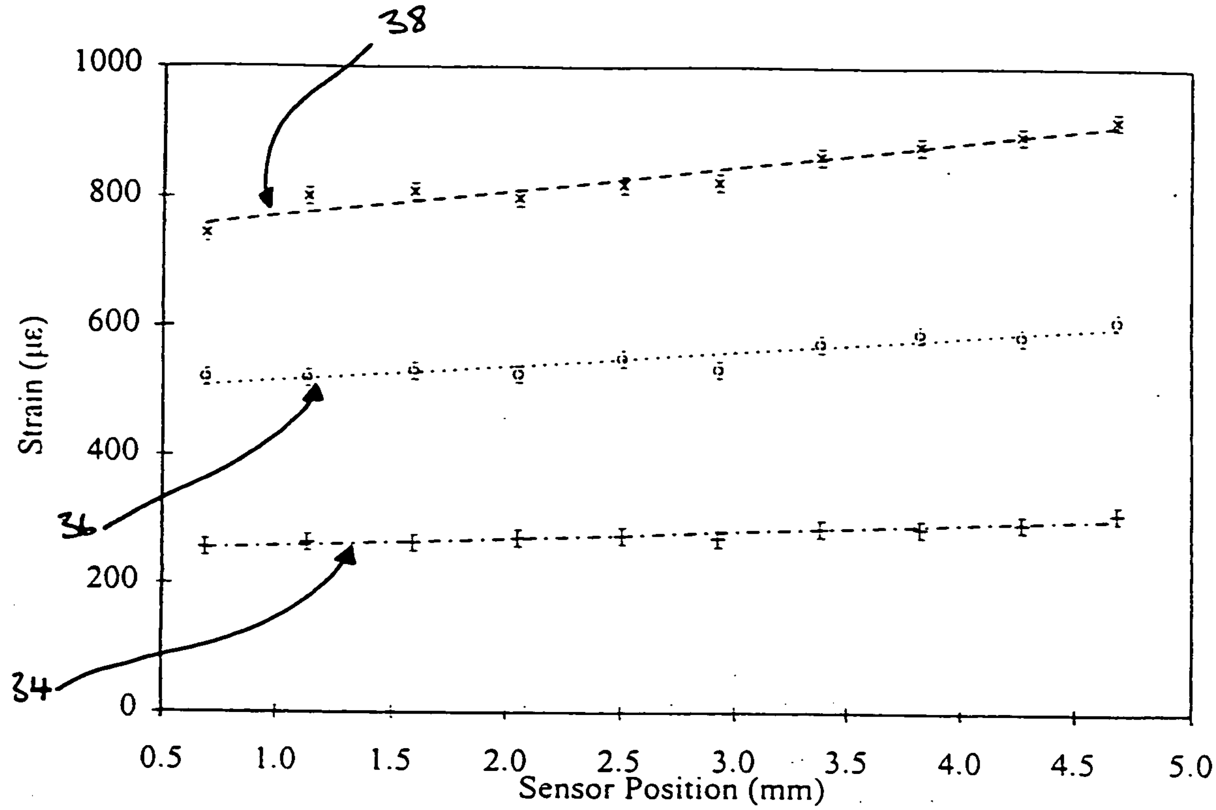

38
1000
800
600
400
200
0
Strain (με)
36
34
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Sensor Position (mm)

FIG 3

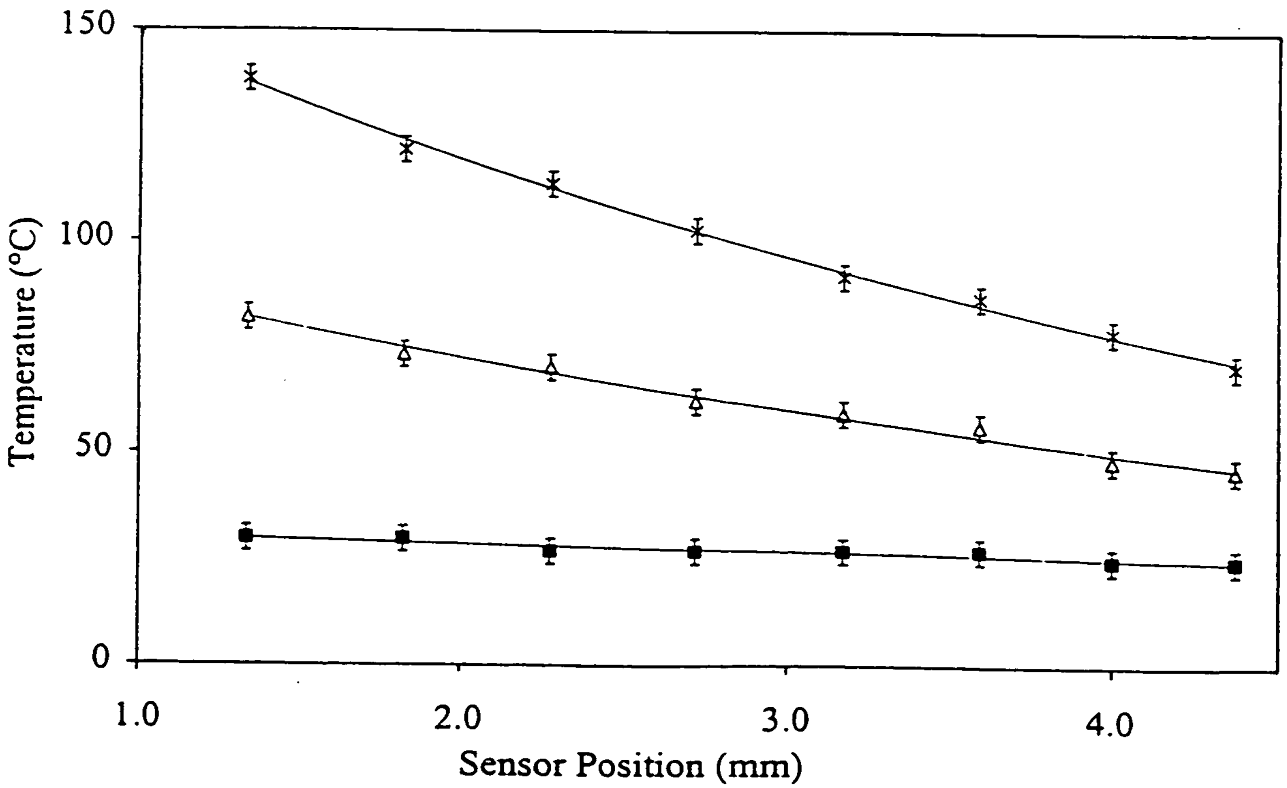

150
100
50
0
Temperature (°C)
1.0
2.0
3.0
4.0
Sensor Position (mm)

FIG 4